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Color Analysis in Air Traffic Control Displays, Part I. Radar Displays

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16. Abstract

One of the current trends in air traffic control (ATC) display technology is a substantial increase in the use of color. Whereas the advantages of color may seem apparent, little attention has been devoted to potential disadvantages of color use with respect to complex cognitive aspects of the ATC environment. Although controllers use several different displays simultaneously (designed and manufactured by different companies), the Federal Aviation Administration (FAA) has not yet adopted a standard for color use to ensure that the various color schemes are compatible. At present, there is no systematic documentation and analysis of color use in ATC displays. This lack of standardization and documentation presents a challenge for manufacturers to design compatible color schemes and for the FAA to evaluate the effectiveness of a display at acquisition. This report was designed to address the lack of such information. The study evaluates color-coding, color usage, task purposes and effectiveness of color use, potential shortcomings, and color complexity for three types of radar displays used by operational controllers. This systematic documentation allowed us to assess compatibility across displays. The study also revealed some visual factors that may affect the usefulness of a display. The results of these investigations will be beneficial for the development of design prototypes and for acquisition evaluation of new ATC display technologies.

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INTRODUCTION

As a result of introducing new technologies into the air traffic control (ATC) system, computer displays have become one of the major sources for air traffic controllers to acquire information and control traffic. Since current display technologies make it easy to render colors on computer monitors, one of the changes in ATC technologies during the past decade is the increasing use of color. At present, the Federal Aviation Administration (FAA) has no requirements on the use of color in ATC displays. Hence, manufacturers of ATC technologies create their own color schemes for their displays or customize display colors to suit their users. These situations raise a number of issues related to the use of color, two of which are addressed in this report.

The first issue pertains to the advantages and drawbacks of color use in individual displays. While the advantages of color seem to be apparent, many display designs do not ensure the advantages of color use in the ATC environment. Moreover, little attention has been paid to potential drawbacks of color use. Xing (2006a) studied color use in a number of ATC facilities and identified several color factors that had the potential to negatively affect task performance. The author developed two checklists to evaluate the effectiveness and drawbacks of color use in ATC displays. These checklists provide a means to systematically evaluate color use across displays.

The second issue is a paradox in ATC technologies: Different manufacturers design the color schemes of individual ATC displays, and they use colors in a display for the benefit of the display in stand-alone conditions. However, most controllers use several displays at their workstation. This report includes displays used at two types of air traffic facilities: the en route air traffic control center, referenced as *en route* facilities, and the terminal radar approach control, referenced as *TRACON* facilities. Typically, a controller uses a primary radar display to monitor and control aircraft and one or several auxiliary displays to acquire additional information for decision-making. For example, operational controllers at some en route facilities use Display System Replacement (DSR) as the primary display; they also use User Request Evaluation Tool (URET), which is placed next to the DSR, to acquire information such as flight status or route. These displays use color to encode information. However, since the color schemes on these displays were developed independently, without respect to each other, color usages can be incompatible between displays. Such incompatibility increases controllers' mental workload and reduces the usefulness of displays. Cardosi (2003) pointed out that compatibility between displays of ATC tools was crucial for controllers to adapt to the tools. Therefore, it is desirable for the FAA and manufacturers to have the proper methods and information resources to ensure display color compatibility.

This study was intended to achieve two goals: 1) to analyze the benefits and drawbacks of color use in some most frequently used ATC displays; and 2) to provide a systematic documentation of color use in primary ATC displays. We first chose to study three primary radar displays for operational controllers to manage aircraft: Automated Radar Terminal System (ARTS) Color Display (ACD), Standard Terminal Automation Replacement System (STARS), and Display System Replacement (DSR). A companion report was focused on auxiliary displays. For each display, this report presents information about color usage, the effectiveness of color use for given tasks, the potential drawbacks of color use, and the overall color complexity of the display.

METHODS

Data Collection

Data about color usage were collected from the displays provided by the FAA William J. Hughes Technical Center. The displays were identical to those currently used in ATC facilities. Color usage and the associated tasks were documented for each display. Because ATC displays were complex and a single display usually had multiple display modes, we documented color usages by the functional components of a display. A spreadsheet was used for data collection in which the elements along the rows of the spreadsheet were the functional components such as background, menus, lists, datablock (text, target, flashing, highlighting, fly-out window), geographic information (boundaries, maps, compass, range rings, etc), weather, and graphic tools; and the elements along the columns were color specification, usage, purpose, redundant cues, and subjective opinions about the efficiency of color use on task performance.

Color Analysis

In a previous study, Xing (2006a) developed two checklists to assess color use in ATC displays. The first checklist, shown in Appendix A, assesses the effectiveness of color. The second checklist, shown in Appendix B, assesses the drawbacks of color use. This study utilizes those checklists to analyze color.

Purposes of Color Use in ATC Displays

To use the checklists, we first needed to determine the purposes of color use. Xing (2006b) identified three main task purposes of color use in ATC displays:

1. Color is used to capture attention. Salient colors are often chosen to encode information that needs to be attended to immediately, such as an alert or emergency.
2. Color is used to identify certain types of information so that searching for the information in complex scenes can be accomplished more effectively. In this application, each color has a distinctive meaning.
3. Colors are used to segment complex scenes in a display so that information belonging to the same category can be organized together. In this application, color is not associated with specific meanings.

Therefore, we referred to the task purposes of color use in three terms throughout this report: *Attention, Identification,* and *Segmentation.* In addition to these purposes, each display has a background color and one or several "default" colors that are used to depict information in its normal status. These colors are not associated with any task purposes and do not have any meanings.

The Checklist for the Effectiveness of Color Use

For each task purpose, the first checklist contains several factors that determine the effectiveness of color. The key factors are:

1. The effectiveness of color for attention is mainly determined by the luminance and chromaticity differences between the color target (to be attended to) and other materials within the view field (Treisman & Gelade, 1980; Nagy & Sanchez, 1992);
2. Identification is mainly determined by the chromaticity differences between the colors and how well the colors can be named reliably (Smallman & Boynton, 1990; Boynton, MacLaury, & Uchikawa, 1989);
3. Segmentation is determined by the uniformity of areas to be segmented and the luminance or chromaticity differences between the areas (Nothdurft, 1993; McIlhagga, Hine, Cole, & Snyder, 1990);
4. The effectiveness of color for any of the three task purposes decreases with the increase of the number of colors (Carter, 1982).

We classified the effectiveness of color use into three categories: "E," effective for the given task purpose; "NE," not effective for the task purpose; and "D," effectiveness of color use depends on other visual attributes. For example, a circle filled with red may or may not be salient enough to draw attention in a colorful complex scene, depending on the size of the circle relative to the sizes of other materials in the scene (Treisman & Souther, 1985).

The Checklist for Potential Negative Effects of Color Use

The second checklist contains the following factors that can negatively affect task performance:

Distraction: Multiple colored targets that need attention are onset simultaneously within the visual field (Simons & Chabris, 1999; DiVita, Obermayer, Nugent, & Linville, 2004).

Coding uncertainty: Messages (text or symbols) identified by colors do not have a unique meaning in identification tasks; thus, color cannot serve as the selection criteria for identification (Jeffrey & Beck, 1972; Green & Swets, 1988).

Loss of integration: Messages in different colors need to be considered together simultaneously for successful task performance (Gegenfurtner, 2004).

Multiple color schemes: 1) One color is used for multiple purposes, or 2) multiple colors represent the same meaning (Poulton & Edwards, 1977).

Experience interference: Color use is against controllers' experience. Typical cases include: 1) red, bright yellow, or orange-red are used to represent non-critical information; 2) dark colors such as black, purple, or brown are used for critical information; 3) green is used to represent specific meanings rather than just indicating messages of normal status; and 4) use of a bright background color (Cohen, Dunbar, & McClelland, 1990; Virzi & Egeth 1985; Cardosi & Hannon, 1999).

Text readability: The luminance contrast between text and background colors is less than the threshold contrast (typically taken as 20%) for error-free reading (Legge, Rubin, & Luebker, 1987; Scharff & Ahumada, 2002).

The factors listed above were used to evaluate each use of color. The potential consequences of these factors on task performance can be found in Appendix B. The six factors were examined for each color usage and the results were classified as either "Y" or "No." "Y" means that the drawback factor exists; thus, the use of this color has the potential of negatively affecting task performance. "No" means that the factor does not exist for the given

color usage; thus, the use of this color does not have the potential of negatively affecting task performance.

Documentation of display-wide color usages

In addition to the analysis of individual color usages, we also documented two aspects of the overall color use in a display: default colors and color complexity. A default color is the one used to depict information in a normal status and is not associated with any particular task. The typical default colors in computer displays are white, black, and green. Color complexity is assessed with three indices:

1. The total number of colors in the display (excluding the background color). For simplification, only the colors differing in chromaticity are counted; in other words, if two colors have the same chromaticity but different luminance, they are counted as one color;
2. The total number of colors used for identification;
3. The number of sets of color-coding, where each set of colors is used to identify different aspects of information.

Since effectiveness is inversely correlated with complexity, the complexity indices reflect the overall effectiveness of color use (Xing, 2006a). Cummings, Tsonis, and Xing (2006) demonstrated that the percentage of performance errors rose if the number of colors used for identification was more than six; while another study indicated that color did not help task performance when more than three sets of color-coding were used in a visual display (Yuditsky, Sollenberger, Della Rocco, Friedman-Berg, & Manning, 2002).

Color Specification

To compute the effectiveness of a color for a given task purpose, we need to determine the luminance and chromaticity specifications of the color. A computer monitor generates a color through three phosphor channels: red, green, and blue. The amount of phosphors emitted from a channel is specified with three digital values: *r, g*, and *b* for red, green, and blue phosphors, respectively. Computer programmers use these three numbers, typically denoted as *rgb* values, to specify a color on a display.

While *rgb* values specify the physical attributes of displayed color, they do not describe how users perceive the color. To describe human color perception, the International Commission on Illumination (CIE) defined color chromaticity coordinates. In this definition, a color can be specified by three variables: *x, y,* and *L,* where *x* and *y* determine the chromaticity, while *L* is the luminance of a color. The *x* and *y* coordinates can vary between 0 and 1. The *xyL* values of a color can be measured with a colorimeter. When measurements are not available, these values can be computed from *rgb* values. The transformations from *rgb* to *xyL* values are described in Appendix C. The chromaticity difference, denoted as *delta C*, between two colors (specified by $x_1\,y_1$ and $x_2\,y_2$) can be computed as $Delta\ C = sqrt((x_1 - x_2)^2 + (y_1 - y_2)^2)$.

RESULTS

This section includes two parts: The first describes the color documentation and analysis for each ATC display. We briefly describe color usages in every functional component, point out the situations where color use was not effective or had potential drawbacks, and analyzed color complexity. The results for each display were presented in a summary table. The second part describes some comparisons of color use across displays.

Color Analysis for Individual ATC Displays

ARTS Color Display (ACD)

ACD is a primary radar display used at TRACON facilities. ACD contains a traffic situation area occupying the majority of the computer screen and a menu bar on the top of the screen. The traffic situation area graphically displays aircraft position symbols and datablocks superimposed on maps, weather, and range rings.

The components of ACD are the background, menus, datablock, range ring, maps, aircraft symbol, and weather. We identified color usage for every component and analyzed their effectiveness as well as drawbacks. The results are presented in Table 1. The order of the elements in the table (from left to right) is components, color, color usage, task purpose, effectiveness, and six drawback factors. The display-wide information about color use in ACD, listed in the bottom portion of Table 1, includes default colors and the three metrics of color complexity (i.e., sets of color-coding, number of colors, and number of color uses).

Below we describe the evaluation results of the color analysis of the ACD. To avoid tedious descriptions, we only focused on the results where the effectiveness of color use was estimated as “NE” (not effective for the task purpose), or “D” (effectiveness of color use depends on other visual attributes), and where the drawback factors were identified as “Y,” indicating there is at least one drawback to the use of color.

Background

Controllers can adjust the background color of the screen for their preference from completely dark to 60% blue. However, most controllers set their screen at a very

dark color. The background color is not associated with any task purpose.

Datablock

A datablock is composed of several short lines of text. Four colors are used to encode the datablock text. Normal (unowned) datablocks are green. Datablocks for owned aircraft (those that are the responsibility of the controller) are white. A datablock in a pointout status is yellow. A controller uses pointouts to identify targets of interest to other controllers. When an aircraft is in a potential collision or conflict situation (with another aircraft or the ground), the red alert text "CA" (Collision Alert) or "LA" (Low Altitude Alert) appears on top of the aircraft's datablock. The alert text blinks until the controller acknowledges it. The red text remains until the conflict is resolved.

Among the datablock colors, white is used to segment datablocks from those in green. It has two potential drawbacks: distraction and loss of integration. Since white datablocks are much brighter than green datablocks, they automatically draw controllers' attention, which reduces controllers' perception of datablocks in other colors. Moreover, green and white colors segregate the owned and unowned aircraft in a controller's mental representation of the traffic situation. Thus, the integration between owned and unowned aircraft is reduced. However, controllers need to consider owned and unowned aircraft together to ensure aircraft separation. This is especially important for those aircraft near sector boundaries. Due to the difference in the colors, controllers may be less likely to detect conflicts between owned and unowned aircraft. Therefore, application of white color to owned datablocks has the potential to cause operational errors.

The red text "CA" or "LA" on the top of a datablock is intended to capture controllers' immediate attention. However, red text is less effective in drawing attention because its luminance is much lower than that of the white and green datablocks. Controllers tend to rely on the blinking signal rather than the color signal to detect the alerts. The red text is also used to identify conflicting datablocks after blinking has stopped. While red is effective to identify datablocks from those in white, green, and yellow, it results in low text readability. The luminance contrast between the red text and black background is about 10%. Many visual studies have demonstrated that the luminance contrast for effortless, error-free text reading should be at least 20% (e.g., Legge et al., 1987).

Menus

The menu bar is located at the top of the screen. It contains a number of text buttons. The background color of the text buttons is gray-blue. Thus, one can easily segment the menu area from the rest of the display. The text is green. The only problem associated with the color use is that the text readability is low. The luminance contrast between green text and the gray-blue background is about 15%. However, since each button has the fixed text at the fixed location, controllers can locate a particular button by remembering the location rather than reading the text, but it takes time and mental resources to learn the location.

Aircraft symbol

The current position of an aircraft is displayed on the ACD with a small graphic symbol. There are two types of symbols: target, denoted to an aircraft that is detected by radar; and beacon, denoted as an aircraft whose position is predicted from the flight plan. All the symbols have the same shape but different colors: slate blue for targets and green for beacons. In addition, the symbol of an aircraft that is currently being scanned by the radar is indicated with dark sky blue. While these colors are used for identification, the chromaticity difference between slate blue and dark sky blue is less than the threshold for effective identification (i.e., users cannot reliably and rapidly identify the information by color). Therefore, they are not effective for the identification purpose. The history trails of aircraft symbols are royal blue. This color is used for the purpose of segmentation.

Weather

Weather information is represented by filled background areas and overlays with datablocks, aircraft symbols, and range rings. ACD provides six weather levels: Levels 1,2 for moderate weather; Levels 3,4 for heavy weather, and Levels 5,6 for severe weather. It is crucial for controllers to distinguish different weather levels. Weather levels are represented by both colors and shades. Levels 1,2 are gray, Levels 3,4 are orange, and Levels 5,6 are orange-red. An area with weather Levels 1, 3, or 5 is uniformly filled with the corresponding color, while levels 2, 4, or 6 are depicted by the respective colors with the stipple addition. It is desirable for controllers to immediately notice heavy / severe weather to make decisions. Thus, orange and orange-red are used to draw attention and to identify weather levels.

The luminance of orange-red is lower than the luminance of the datablocks; thus, the color signal itself is not adequate to draw attention. In this case, the effectiveness of the color depends on the size of the filled area. Only when the orange-red area is comparable to or significantly larger than the area of individual datablocks can it be salient enough to draw attention. Otherwise it will not

pop out from other displayed materials. The same analysis applies to orange color for weather levels 3 and 4.

The text readability of datablocks on a filled area of weather can become very low given that the text and background colors of white vs. gray, red vs. orange, and red vs. orange-red are all below the threshold contrast (i.e., 20%) for error-free reading. Therefore, if an aircraft flies into a heavy weather area, controllers may find it difficult to read the datablock. However, controllers have to be able to read the information in the datablocks, as aircraft information may change more rapidly than weather.

Display-wide information

The display-wide information about color use in ACD is shown in the bottom portion of Table 1. The default color is green. Three sets of colors are used for identification tasks in which controllers have to remember the meaning of colors. Those are (gray, orange, orange-red) for weather levels, (green, slate blue, dark-sky blue) for aircraft symbols, and (white, yellow, red) for datablocks. When counting the number of colors, we only considered those varying in chromaticity but not in luminance. For instance, a dark green and a light green were counted as one color as long as they had the same chromaticity. Also, the background color of the display was not counted. Finally, the total number of color uses is 14 while the total number of colors is 12. The difference between the number of color uses and total number of colors indicates that some colors are used more than once to represent different types of information. For example, green is used in the menu, datablock, and some aircraft symbol components.

Standard Terminal Automation Replacement System (STARS)

STARS is also a primary display used in terminal facilities. The basic layout of a STARS display has the same format as that of ACD; however, STARS has more display components. The menu bars, system status alert, and coordination list are located along the top and left edges of the STARS display. The traffic situation area shows datablocks, aircraft symbols, geometric graph (maps, range rings, compass, and predicted track line), weather, and geographic restriction areas. Color is essentially used in every component. We presented the results of color analysis for STARS in Table 2 (formatted like Table 1). Below we described the situations where color use was either not effective for a given task or had potential to negatively affect task performance.

Toolbar (menu bars)

The menu bars of STARS use nine colors. The background color of the menu bars is gray-green. It segments the menu area from the traffic situation area. The background color of the text buttons on the menu bars is dark green. The color differentiates buttons from the background of menu bars. When a button is selected, its background color becomes "selected dark green," which has the same chromaticity as the dark green but a higher luminance. The default color for menu text is white. Highlighted text is displayed in bright yellow. The purpose of the highlighted yellow is to draw attention. However, yellow has a lower luminance than white; therefore, yellow is not effective to draw attention away from white text. Blue-gray and selected blue-gray are used to identify the different status of weather level selections. However, the luminance difference between the two colors is not effective as a selection criterion for identification. Finally, most of the colors in the menu bars have a common drawback factor: They are used more than once to represent different types of information in STARS, as described later.

System status alert

The system status alert is a text box in the menu area. Within the box are text fields for system failure alert, system overload alert, and radar failure alert. The background of the box is black. If an alert is issued, red alert text appears in the corresponding field of the box. Red is used to draw the controller's attention to the alert. However, red text is not salient enough to draw attention because of its low luminance. In addition, the luminance contrast of the red text on the black background is less than the threshold contrast for error-free reading.

Lists

STARS provides controllers with a number of lists containing various types of traffic information. The lists can be displayed by clicking the buttons in menu bars. The titles of the lists are blue-gray, the same color used for the weather selection buttons on the menu bars. Also, the luminance contrast of the blue-gray text on the black background is below the threshold contrast for error-free reading.

Coordination list

The coordination list provides information about the coordination status between controllers. The list uses three colors to indicate the status of coordination texts: white for unsent messages, green for acknowledged messages, and yellow for unacknowledged messages. The purpose of these colors is identification. A drawback is that these colors are also used to represent other information on STARS.

Table 1: Color Documentation and Analysis for ARTS Color Display (ACD)

These symbols in Tables 1-3 represent the longer words:

dis — distraction
unc — coding uncertainty
int — loss of integration
mul — multiple color schemes
exp — experience interference
read — text readability
Att — Attention
Iden — Identification
Seg — Segmentation
Eff — Effectiveness
E — Equally effective
NE — Not effective
NA — Not Applicape
D — The effectiveness of color depends on other factors
Y — Yes

Component		**Color**	**Usage**	**Purpose**	**Eff**	**Drawback factors**					
						Dis	**Unc**	**Int**	**Mul**	**Exp**	**Read**
Background		Black / blue	Filled screen	NA	NA	NA	NA	NA	NA	No	NA
Menus	Back-ground	Gray-blue	Text box	Seg	E	No	No	No	No	No	NA
	Text	Green	Text	Default	NA	No	No	No	No	No	Y
Datablock	Unowned	Green	Text	Default	NA	No	No	No	No	No	No
	Owned	White	Text	Seg	E	Y	No	Y	No	No	No
				Iden	E						
	Point-out	Yellow	Text	Iden	E	Y	No	Y	No	No	No
	Alert	Red	Text	Att	NE	No	No	No	No	No	Y
				Iden	E						
Range rings		Gray	Curve	Seg.	E	No	No	No	No	No	No
Maps		Wheat	Line	seg	E	No	No	No	No	No	No
Aircraft symbol	Beacon	Green	Shape	Iden	E	No	No	No	Y	No	No
	Target	Slate blue	Shape	Iden	NE	No	No	No	Y	No	NA
	Current scans	Dark-sky blue	Shape	Iden	NE	No	No	No	Y	No	NA
	History trail	Royal blue	Shape	Seg	E	No	No	No	No	No	NA
Weather	Levels 1,2	Gray	Filled area	Iden	E	No	No	No	No	No	Y
	Levels 3,4	Orange	Filled area	Iden	E	No	No	No	No	No	Y
				Att	D						
	Levels 5,6	Orange-red	Filled area	Iden	E	No	No	No	No	No	Y
				Att	D						
	Stipple	Gray	Dot	Seg	E	No	No	No	No	No	NA
Default colors		Green									
Sets of color-coding		(White, Yellow, Red) for datablocks (Green, Slate blue, Dark-sky blue) for aircraft symbols (Gray, Orange, Orange-red) for weather levels									
Number of colors		12									
Number of color usages		14									

Table 2: Color Documentation and Analysis for Standard Terminal Automation Replacement System (STARS)

Component		Color	Usage	Purpose	Eff	Drawback factors					
						Dis	Unc	Int	Mul	Exp	Read
Background		Dim gray /black	Filled screen	NA	NA	NA	NA	NA	NA	No	NA
Toolbar (Menu bar)	Background	Gray green	Filled area	Seg	E	No	No	No	Y	No	NA
	Button background	Dark green	Filled box	Seg	E	No	No	No	Y	No	NA
	Selected background	Selected dark green	Filled box	Seg	E	No	No	No	Y	No	NA
	Button shadow top	Dark gray	Filled area	NA	NA	NA	NA	NA	NA	No	NA
	Button shadow bottom	Black	Filled area	NA	NA	NA	NA	NA	NA	No	NA
	Normal text	White	Text	Default	NA	No	No	No	Y	No	No
	Highlight text	Bright yellow	Text	Att	NE	No	No	No	Y	No	No
	WX available & site unavailable	Blue-gray	Filled box	Iden	NE	No	No	No	Y	No	No
	WX selected	Selected blue-gray	Filled box	Iden	NE	No	No	No	Y	No	No
System status alert		Red	Text	Att	NE	No	No	No	No	No	Y
System status weather		Cyan	Text	Iden	E	No	No	No	No	No	No
Lists	Title	Blue-gray	Text	Seg	E	No	No	No	Y	No	Y
	text	Green	Text	Default	NA	No	No	No	No	No	No
Coordination list	Unsent	White	Text	Iden	E	No	No	No	Y	No	No
	Acknow-ledged	Green	Text	Iden	E	No	No	No	Y	No	No
	Unacknow-ledged	Yellow	Text	Iden	E	No	No	No	Y	No	No
Geographic restriction Area	Background	Beige	Filled area	Seg	E	No	No	No	No	No	NA
	Text	Green	Text	Default	NA	No	No	No	No	No	Y
Datablock	Normal	Green	Text	Default	NA	No	No	No	No	No	No
	Highlighten	White	Text	Seg	E	No	No	No	No	No	No
	Alert	Red	Text	Att	NE	No	No	No	No	No	Y
				Iden	E						
Geometric graph	Range rings	Green	Line	Default	NA	No	No	No	No	No	NA
	Compass	Green	Line	Default	NA	No	No	No	No	No	NA
	Predicted track line	Green	Line	Default	NA	No	No	No	No	No	NA
	Maps	Yellow	Line	Seg	E	No	No	No	No	No	NA

(Continued on next page)

Table 2: Color Documentation and Analysis for Standard Terminal Automation Replacement System (continued)

Aircraft symbol	Beacon	Bright yellow	Shape	Iden	E	No	No	No	Y	No	NA
	Search target	Green	Shape	Iden	NA	No	No	No	Y	No	NA
	Current scans	White	Shape	Iden	E	No	No	No	Y	No	NA
	History trail	Green	Shape	Seg	E	No	No	No	No	No	NA
Weather	Level 1,2,3	Dark gray blue	Filled area	Iden	NE	No	No	No	No	No	Y
	Level 4,5,6	Dark mustard	Filled area	Iden	E	No	No	No	No	Y	Y
	stipple	Gray	Texture	Seg	E	No	No	No	No	No	NA
Default colors		Green for traffic situation area and white for toolbar area									
Sets of color-coding		(Dark gray-blue, Dark mustard) for weather levels (Bright yellow, White, Green) for aircraft symbols (Yellow, White, Green) for coordination list (Red, green, white) for datablocks (Red, black) for system status alerts (Blue-gray, Selected blue-gray) for weather buttons on the menu bar									
Number of colors		15									
Number of color usages		31									

Datablock

Normal datablocks are green text. A controller can highlight a specific datablock by clicking it to temporarily change the text color to white. The alert messages about potential collisions are similar to those used on the ACD. Other than the red text of "CA" and "LA," the alert messages of STARS also include other types of alert in blinking red. Like in ACDs, the red alert text alone is not salient enough to draw attention. However, the blinking signal is an effective visual attribute to gain attention. The red text also has low text readability.

Aircraft symbol

An aircraft symbol may consist of a search target symbol, or a beacon target symbol, or both. A search target symbol is green and a beacon target symbol is bright yellow. In addition, white is used to identify the symbol of an aircraft that is at the current scan position. Thus, the purpose of bright yellow, green, and white is to identify different types of symbols. The drawback is that each color had multiple uses in STARS.

Weather

Weather information is presented on STARS with filled background areas that are overlaid with datablocks and aircraft symbols. Six levels of weather precipitation are displayed independently or simultaneously, based on weather selection. Combinations of overlaying stipple and colors are used to discriminate weather intensity levels. Controllers can determine each weather level in isolation based on the coding used. The coding scheme for weather levels is as follows:

Weather Level 1 – dark gray-blue

Weather Level 2 – dark gray-blue, low density gray overlay stipple

Weather Level 3 – dark gray-blue, high density gray overlay stipple

Weather Level 4 – dark mustard

Weather Level 5 – dark mustard, low density gray overlay stipple

Weather Level 6 – dark mustard, high density gray overlay stipple

Weather information is shown with these two low luminance colors to allow controllers to see aircraft datablocks, list data, aircraft symbols, and map data through the weather data. However, the readability of red alert messages in datablocks is below the error-free reading threshold when overlaid on dark gray-blue or dark mustard filled areas. Dark gray-blue for weather levels 1,2,3 is not effective in identification because the chromaticity difference between dark gray-blue and dark blue (the background color) is less than the threshold. Another drawback is that the use of mustard for Levels 4,5, and 6 may interfere with controllers' experience of color use.

While Levels 4,5,6 represent heavy or severe weather, dark colors like mustard typically iminates non-critical information, so mustard may not alert controllers.

Geographic restriction area

A restriction area is indicated with a beige-filled circle or polygon. The text displayed within the circle or polygon is green. Controllers tend to rely on the shape rather than the color to identify geographic restriction areas. Because the shapes are distinctive from other materials on the display and can be reliably named (circle or polygon), they can be as effective as color for identification tasks. Thus, the purpose of the color was classified as segmentation, as the color is used to segment a restricted area from its surroundings. The readability of the green text on a beige background is below the threshold contrast for error-free reading.

Display-wide information

The display-wide information about color use in STARS is shown in the bottom portion of Table 2. The default colors are green for the traffic situations and white for the information in menu bars. Five sets of colors are used for identification. Notice that many colors are associated with multiple meanings. A total of 15 colors are used in STARS, while the total number of color uses is 31. Many colors used in STARS have chromaticity values that are too close to be distinctively and reliably named. For instance, users would have difficulty in distinctively naming several colors "gray-blue," "blue-gray," "slate-blue." Therefore, while those colors can be used for the purpose of segmentation, they should not be used to identify categories of information.

Display System Replacement (DSR)

DSR is currently the primary display in most en route facilities. Like other primary displays, DSR has menu bars along the display and a traffic situation area on the central portion. The background color of a DSR display can be changed by controllers from dark blue to black. Datablocks and aircraft symbols are green. Alerted datablocks are indicated with blinking text. Only three components of a DSR display use color-coding: the weather display, fly-out window, and graphic tool. Below we describe the color analysis for these components. The summarized results of this analysis are presented in Table 3.

Weather and Radar Processor (WARP) display

WARP presents specialized aviation weather products to support en route air traffic control operations. WARP provides Next Generation Doppler Weather Radar (NEXRAD) data for DSR with five weather levels: Level 2 for moderate weather; Levels 3,4 for heavy weather, and Levels 5,6 for severe weather. Weather levels are represented by two colors and one color pattern: Level 2 is purple, Levels 3,4 are turquoise and black checkboard;

Table 3: Color Documentation and Analysis for Display System Replacement (DSR)

Component	Color	Usage	Purpose	Eff	Drawback factors					
					Dis	Unc	Int	Mul	Exp	Read
Background	Dark blue	Filled whole screen	NA	NA	NA	NA	NA	NA	No	NA
Weather (WARP)	Purple	Filled area	Iden	E	No	No	No	No	No	Y
	Turquoise-black	Filled checkboard	Iden	D	No	Y	No	No	No	Y
	Turquoise	Filled area	Iden	D	No	Y	No	No	Y	Y
			Att	E						
Fly-out window	Brown	Text box	Seg	E	No	No	No	No	No	Y
Graphic tool	Red	Filled area, text	Iden	E	No	No	No	No	Y	Y
	Yellow	Filled area, text	Iden	E	No	No	No	No	No	No
	Green	Filled area, text	Iden	NE	No	No	No	No	Y	No
	White	Filled area, text	Iden	E	No	No	No	No	No	No
Default color	Green									
Sets of color-coding	(Red, Green, Yellow, White) for graphic tool (Purple, Turquoise) for weather									
Number of colors	8									
Number of color usages	9									

and Levels 5,6 are turquoise. The color scheme for WARP has several drawbacks:

1. Coding uncertainty in the use of turquoise. A user has to use the pattern cue to identify Level 3,4 weather from Level 5,6 weather.
2. Low readability. The text of green datablocks has a low readability when overlaying with filled weather areas.
3. Experience interference. The presence of Level 5,6 weather is a critical event that requires controllers' attention or alert. However, it was represented by turquoise, a color that usually would not trigger an alert.

Fly-out window

By clicking a datablock, a fly-out window appears next to the datablock. The window displays a column of altitude numbers for controllers to change the altitude of the aircraft in the flight plan (but does not cause the pilot to change altitude). The background of the window is white and the altitude text is black. The current altitude of the aircraft is highlighted with a brown text box. The luminance contrast of the black text on the brown background is below the threshold for error-free reading. However, controllers do not really need to read the current altitude. They tend to use the brown color as a reference mark: Moving up from the mark increases the altitude and moving down decreases the altitude.

Graphic tool

The graphic tool allows controllers to pick up one of four colors to draw filled areas for specific flying regions. The route and distance from a given flight to a specified region is subsequently displayed with the same color. Thus, the colors are used for identification. The four colors are red, yellow, green, and white. Among them, green is not effective for identification because the default text color of the display is green. One drawback of the color use is experience interference, that is, red should be reserved only for critical information. Using red to label non-critical information is inconsistent with controllers' experience of color use. In addition, the readability of the red text on the dark background is below the threshold for error-free reading. Another drawback is that the use of green for identification is inconsistent with the convention of color use, as green is typically used as a default color and should not be assigned to specific meanings.

Display-wide information

The display-wide information about color use in DSRs is presented in the bottom portion of Table 3. The default color is green. Only seven colors are used in DSRs. The total number of color uses is eight. Only two sets of colors are used for identification: (red, green, yellow, and white) for the graphic tool and (purple, turquoise) for weather.

Comparisons of Color Use in ATC Displays

Effectiveness and drawbacks

To compare the effect of color across displays, we calculated the number of situations in which color use is not effective for a given task purpose, or the effectiveness depends on other attributes besides color. That is, we counted the number of times "NE" and "D" appeared in the "Eff" column in each of the summary tables. We also calculated the number of drawback factors for each display, that is, the number of times "Y" occurred in the six right-most columns in each table. These two numbers together can reflect the overall effectiveness of color use in a display. Figure 1 shows the results. The upper and lower panels are for the effectiveness and drawbacks, respectively. From left to right along the horizontal axis are the three displays: ACD, STARS, and DSR. The vertical axis of the upper panel represents the number of situations where color use is either not effective or the effectiveness depends on other visual attributes (i.e., the number of "NE" and "D"). The vertical axis of the lower panel represents the number of situations where color use has the potential to negatively affect ATC task performance (i.e., the number of "Y" in drawback factors). Figure 1 indicates that DSR has the lowest number of color use problems. In addition, while both ACD and STARS are the primary displays for terminal facilities, STARS has more problems in color use than ACD.

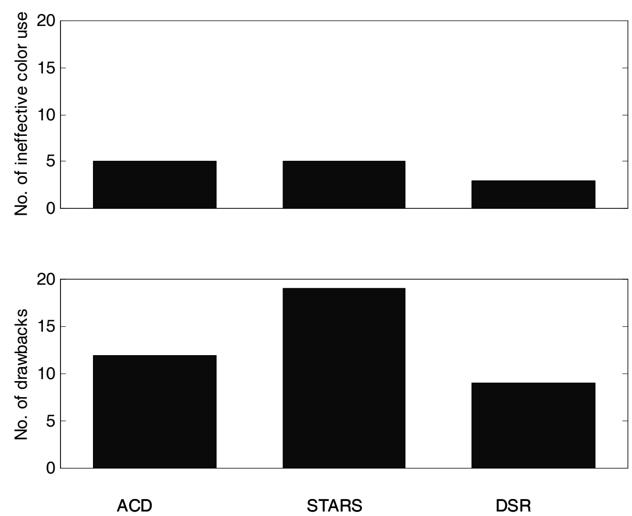

Figure 1: Effectiveness and drawbacks of color use in three primary ATC displays. The upper and lower panels are for effectiveness and drawbacks, respectively. The three displays are listed along the horizontal axis, with ACD, STARS, and DSR from left to right.

Notice that the two variables shown in Figure 1 are rough estimates of the effects of color in displays. Since the effectiveness and drawback factors are assessed on a simple yes / no scale, the results cannot accurately reflect the effects of a color use on task performance. In other words, two color uses that have "Yes" in the same drawback factor category may not affect controllers' task performance to an equivalent degree. We will discuss this in detail later.

Color complexity

Three indices were used to measure color complexity: the number of colors, the number of color uses, and the number of sets of color-coding. For any given task purpose, the effectiveness of color decreases with the increase of these indices (Xing, 2006a). Specifically, visual studies have demonstrated that the number of colors in a display should be fewer than 6~7. Beyond that, color has no advantage compared with achromatic attributes (Carter, 1982). Also, Yuditsky et al. (2002) showed that color had no advantage when three sets of color-coding were used simultaneously to encode different parts of datablocks. Finally, the number of color uses provides a rough index of the mental workload imposed by colors.

Figure 2 shows the three indices for each of the three displays (ACD, STARS, and DSR) and the corresponding upper-limits beyond which the effectiveness of color begins to decrease, if not completely diminish. In each panel, the vertical axis represents the overall index. The three displays are listed along the horizontal axis; from left to right are ACD, STARS, and DSR. The dashed horizontal line in the top and bottom panels each represents a saturation number beyond which the effectiveness of color begins to decrease. The upper-limit for the number of colors is six and the upper-limit for the number of color-coding sets is three, inferred from the literature cited previously. No data about the saturation number of color usages is available. Figure 2 shows that DSR is the only display that uses colors below the saturation lines. The other two displays use color beyond the one or both saturation lines, suggesting that the effect of color is not optimal for ACD and STARS.

DISCUSSION AND CONCLUSIONS

This study analyzed color use for three primary ATC displays. It represents the first attempt to evaluate the efficiency of ATC technologies by using the same format of analysis across multiple displays. Some manufacturers provide information about color usage in their display interface specifications. However, such documents are not always available to other designers and FAA human factors practitioners. Also, the descriptions about color usage are often incomplete and not systematic. Moreover, manufacturers' documentation does not provide information about the effectiveness and drawbacks of color use. Therefore, the information provided by this report is expected to benefit the design and evaluation of new ATC technologies.

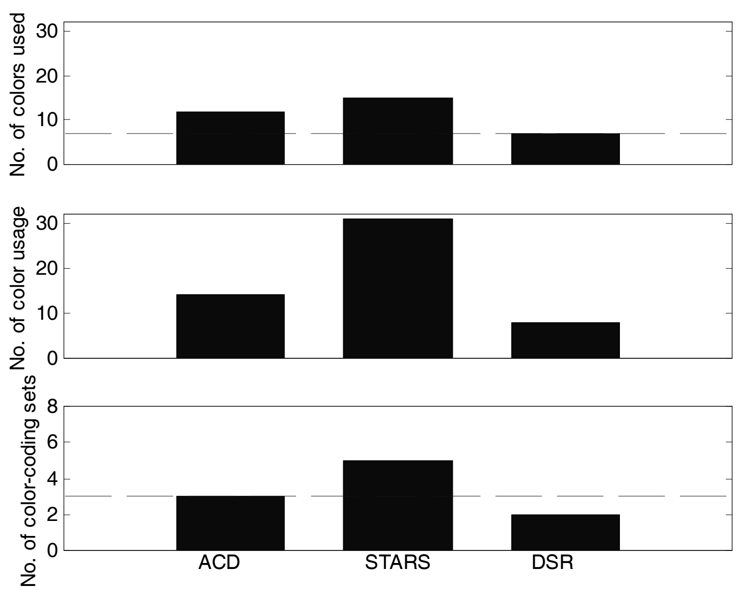

Figure 2: Color complexity in the three primary ATC displays. The top, middle, and bottom panels correspond to the numbers of colors, color usages, and sets of color-coding, respectively.

Operational Effects of Drawbacks of Color Use in ATC Displays

A shortcoming of this study is that we only provided information about drawbacks of color use with a simple yes/no scale. Visual and cognitive researchers have studied the possible consequences of the drawback factors (Xing, 2006a). However, most of those results were obtained through simplified lab experiments and may not be directly applicable to ATC operations. Therefore, even when a drawback factor for a color usage is identified, it may or may not produce a negative effect in real ATC operations. For example, in the DSR fly-out window, it is difficult to read the black text of the current altitude on the brown background. Thus, the factor of text readability was identified as "Y" for that color usage in Table 3. However, controllers do not need to read the current altitude from the fly-out window. They only use the brown color as a reference mark to choose a new altitude. Hence, for those factors with a "Y" in Tables 1-6, the operational consequences can vary from case to case. The factor may distract controllers in some ways, such as increasing mental workload moderately, but the overall negative impact is negligible. Alternatively, the factor may potentially contribute to operational errors. Therefore, a future study should analyze operational drawbacks of the color use identified in this report.

Limitations of the Analysis

The analysis we performed in this study was for ideal viewing conditions, assuming that controllers have normal color vision and that computer monitors render colors as described in manufacturers' manuals. However, ATC operations are not always performed under those ideal conditions. The current FAA's color vision standard allows personnel with a certain degree of color vision deficiencies to enter into the controller workforce. While the issue of color vision deficiencies was beyond the scope of this report, developers of ATC technologies need to be aware of the potential effects on controllers with a color vision deficiency.

On the equipment side, several factors may affect the displayed colors:

1. Controllers can adjust the brightness of their computer screens. When the brightness is reduced, some low-luminance colors (such as those used for weather on DSR and STARS) may become invisible to controllers.
2. The displays used in air traffic control towers are often viewed under strong ambient light. In those situations, the colors may appear "washed out" so the color-coding becomes ineffective.
3. ATC displays are often viewed from off-axis view angles but different view angles cause significant variations in displayed colors on flat-panel displays. Therefore, when viewed from off-axis angles, text and graphics may have a loss of luminance contrast and undesirable variations in color.

Because of the presence of color deficient controllers and those undesirable, but inevitable, viewing conditions, it is always important that the use of color in ATC displays should be accompanied by achromatic redundant cues. The use and effectiveness of redundant cues in ATC displays have been separately addressed in another report (Xing, 2006c).

CONCLUSIONS

This report has achieved several goals. First, it provided a systematic documentation of color use in three ATC displays. Manufacturers and interface designers in ATC facilities can use this document as a reference to improve compatibility and consistency of their new ATC products to existing operational displays. Also, such a document can be used for other aviation research, such as the development of color vision standards for air traffic control specialist applicants. Second, it provides analytic results about the effectiveness and drawbacks of color use in ATC displays. Such information is useful for the evaluation of proposed automation systems at acquisition. Third, the results can help display users (training supervisors and controllers at ATC facilities) to become aware of potential negative consequences of color use so that they can try to avoid situations where a color use can contribute to operational deviations and errors. Finally, this study provided a general method for human factors practices in the design and evaluation of human-computer interaction systems.

REFERENCES

Boynton RM, MacLaury R, Uchikawa K (1989). Centroids of color categories compared by two methods. Color Res. Appl. **14**: 6-15.

Cardosi K (2003). Human factor integration challenges in the terminal radar approach control (TRACON) environment. Washington, DC: Federal Aviation Administration; Technical Report No. DOT/FAA/AR-02/127.

Cardosi K, Hannon D (1999). Guidelines for the use of color in ATC displays. Washington, DC: Federal Aviation Administration; Technical Report No. DOT/FAA/AR-99/52.

Carter RC (1982). Visual search with color. J Exp Psychol. 8: 127-136.

Cohen JD, Dunbar K, McClelland JL (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. Psychol Rev. 97(3): 332-61.

Cummings, Tsonis, Xing J (2006). Washington, DC: Federal Aviation Administration; Technical Report. In press.

DiVita J, Obermayer R, Nugent W, Linville JM (2004). Verification of the change blindness phenomenon while managing critical events on a combat information display. Hum Factors. 46(2): 205-18.

Gegenfurtner KR (2004). Cortical mechanisms of color vision. Nat Rev Neurosci. 4: 563-72.

Green DM, Swets JA (1988). Signal Detection Theory and Psychophysics. Los Altos, CA: Peninsula Publishing.

Jeffrey TE, Beck FJ (1972). Intelligence information from total optical color imagery. U.S. Army Behavior and System Research Laboratory, Research Memorandum, 72-4.

Julesz B (1965). Texture and visual perception. Sci Am. 38-55.

Legge GE, Rubin GS, Luebker A (1987). Psychophysics of reading–V. The role of contrast in normal vision. Vision Res. 27(7): 1165-77.

McIlhagga W, Hine T, Cole GR, Snyder AW (1990). Texture segregation with luminance and chromatic contrast. Vision Res. 30(3): 489-95.

Nagy AL, Sanchez RR (1992). Chromaticity and luminance as coding dimensions in visual search. Hum Factors. 34(5): 601-14.

Nothdurft HC (1993). The role of features in preattentive vision: comparison of orientation, motion and color cues. Vision Res. 33(14): 1937-58.

Poulton EC, Edwards RS (1977). Perceptual load in searching for sloping colored lines camouflaged by colored backgrounds: A separate-groups investigation. J Exp Psychol Hum Percept Perform. 3(1): 136-50.

Scharff LF, Ahumada AJ Jr (2002). Predicting the readability of transparent text. J Vis. 2(9): 653-66.

Simons DJ, Chabris CF (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. Perception. 28(9): 1059-74.

Smallman HS, Boynton RM (1990). Segregation of basic colors in an information display. J Opt Soc Am A. 7(10): 1985-94.

Treisman AM, Souther J (1985). Search asymmetry: a diagnostic for preattentive processing of separable features. J Exp Psychol Gen. 114(3): 285-310.

Treisman AM, Gelade G (1980). A feature-integration theory of attention. Cognitive Psychol. 12(1): 97-136.

Virzi RA, Egeth HE (1985). Toward a translational model of Stroop interference. Mem Cog. 13(4): 304-19.

Xing J (2006a). Color and visual factors in ATC displays. Washington, DC: Federal Aviation Administration Office of Aerospace Medicine; Technical Report No. DOT/FAA/AM-06/15.

Xing J, Schroeder DJ (2006b). Reexamination of color vision standards. I. Status of color use in ATC displays and demography of color-deficit controllers. Washington, DC: Federal Aviation Administration Office of Aerospace Medicine; Technical Report No. DOT/FAA/AM-06/2.

Xing J (2006c). Reexamination of color vision standards. III. Analysis of the effects of color vision deficiencies in using atc displays. Washington, DC: Federal Aviation Administration Office of Aerospace Medicine; Technical Report No. DOT/FAA/AM-06/11.

Yuditsky T, Sollenberger R, Della Rocco P, Friedman-Berg F, Manning C (2002). Application of color to reduce complexity in air traffic control. Atlantic City, NJ: Federal Aviation Administration William J. Hughes Technical Center; Technical Report No. DOT/FAA/CT-TN03/01.

APPENDIX A

Table A-1. A Checklist for the Effectiveness of the Use of Color in ATC Displays

Task purpose	Color and visual factors	Conditions for color-use being effective	Yes / No
Attention	Luminance	The luminance of the color-coded target is greater than or equal to that of distractors (i.e., other materials displayed in the visual field).	
	Luminance and chromaticity	The luminance difference between the color-coded target and distractors is greater than 20cd/cm^2 regardless the chromaticity difference. Alternatively, the chromaticity difference between the color-coded target and distractors should be greater than 0.24 in CIE chromaticity coordinates.	
	Number of distractor colors	The number of distractor colors should be less than 3~4 (The number of colors of the distractors with a size greater than or equivalent to that of the target should be minimized).	
Identification	Color naming	The colors used for identification can be named uniquely and consistently.	
	Chromaticity	The chromaticity differences between the colors are greater than 0.036.	
	Luminance	The luminance differences between colors are less than 20cd/cm^2.	
	Number of set colors	The number of colors is less than 7.	
Segmentation	Luminance or Chromaticity	For regional object segmentation, the chromaticity difference between the object and its surrounds is greater than 0.004. Alternatively, the luminance ratio, defined as the absolute luminance difference between the object and surrounds divided by the luminance of the object, is greater than ~5%. For pattern segmentation, the color difference between the pattern and its surrounds is greater than 0.02. Alternatively, the luminance ratio is greater than 15~20%.	
	No. of object colors	The number of colors of the object to be segmented is less than 2 unless the object is composed of a regularly patterned texture of different colors.	

APPENDIX B

Table B-1. A Checklist of Drawbacks of Color Use in ATC Displays

Color and visual factor	**Conditions for inducing drawbacks**	**Potential consequences induced by the factor**	Yes / No
Distraction	Multiple colored targets for attention are onset simultaneously within the view field.	Only one of the targets captures attention; others could be ignored.	
Coding uncertainty	Messages (text or symbols) identified by colors do not have a unique meaning; thus, color cannot serve as the selection criteria.	Slower and less accurate in identification compared to using text or symbols alone.	
Loss of integration	Color-segmented messages need to be considered together simultaneously for task performance.	Less chance to associate pieces of information that are color segmented.	
Multiple color schemes	1) More than 3 sets of color-coding in a display.	Increasing chances of missing information; users tend to ignore color-coding.	
	2) One color is used for multiple purposes, or multiple colors are used for the same purpose.	Increasing cognitive workload; slower in interpreting information; increasing chances of misinterpreting information.	
Experience interference	Color use differs from controllers' experience (such as red for non-critical information).	Increasing chances of misinterpreting information.	
Text readability	The luminance contrast between the text and background colors is less than the threshold contrast (20~30%) for error-free reading.	Reducing reading speed; increasing reading errors.	

APPENDIX C

Transformations Between Digital Values of a Displayed Color and CIE Chromaticity Coordinates

Colors in a computer display can be described by the tri-stimulus color system. This system specifies a color with three photometric quantities: R, G, and B. Given (r, g, b) as the 8-bit digital values for each of the red, green, and blue channels of a monitor, the relationship between RGB values and digital values is determined by the following equations:

$R=(r/255)^{gamma}$

$G=(g/255)^{gamma}$

$B=(b/255)^{gamma}$

Where Gamma is a parameter of a monitor that specifies the nonlinear relationship between the *rgb* values and the rendered luminance. The Gamma value for CRT displays generally varies in the range of 1.8~2.5, with a typical default value of 2.2.

And,

$X=40.9568*R + 35.5041*G + 17.9167*B;$

$Y=21.3389*R + 70.6743*G + 7.98680*B;$

$Z=1.86297*R + 11.4620*G + 91.2367*B.$

Note that the parameters in these transformations vary from monitor to monitor. We will use these default values for the computation in this report.

Then,

$x=X/(X+Y+Z);$

$y=Y/(X+Y+Z);$

$L=Y$